

## STUDIES OF REACTION CONTROLS

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The attitude-control method selected for the North American X-15 for flight at extremely low and zero dynamic pressures utilizes the reaction forces developed by small-rocket units located on the airplane to produce rolling, pitching, and yawing moments. An investigation of reaction controls similar to those selected for the X-15 has shown that unique control problems exist for flight at the low dynamic pressures where this type of control is used. Although the Bell X-1B configuration was utilized for this investigation, a range of variables was covered to determine the significant effects of various factors on flight with reaction controls. It was also of interest to determine fuel requirements for the rocket units. The investigation consisted of analog-computer studies and ground-simulator tests. The significant results of this investigation will be discussed. ✓

The general areas for flight with reaction controls are presented in figure 1 which shows the Mach number and altitude relationship for dynamic pressures  $q$  of 2.5 and 10.0 lb/sq ft. Curves showing the performance of the X-1B and X-15 airplanes are also included in figure 1. Other studies have shown that aerodynamic controls will be effective at dynamic pressures greater than about 10.0 lb/sq ft. The shaded region for  $q$ , from 2.5 to 10.0 lb/sq ft, is an area where either control may be used. Reaction controls will be required for flight at dynamic pressures less than  $q = 2.5$  lb/sq ft. A rather limited region for reaction controls can be explored with the X-1B, but the X-15 will be able to operate over a wide region where reaction controls will be required.

A three-degree-of-freedom analog-computer simulation was initially made for conditions of  $q = 0$  in order to eliminate the many additional variables that would be covered if the aerodynamic terms were included.

Figure 2 shows the type of control stick and pilot presentation used. Roll and pitch control were applied by normal hand movement; and yaw control, by a thumb switch. The control stick was not an optimum configuration but after practice pilots became proficient in its use. A small oscilloscope presented roll and pitch angles in a manner similar to the conventional gyro horizon, and a separate instrument needle presented yaw angle.

Simulated flights of 2-minute duration were made in which the airplane was initially disturbed slightly and the pilot was required to stop

motion and maintain steady flight at an attitude of zero for roll, pitch, and yaw. For this 2-minute flight, results were evaluated from pilots' comments and from the impulse.

The investigation was first concerned with the choice of control configuration, or proportioning of control thrust to stick deflection. The variations covered are shown in figure 3. On the left are the proportional controls with a linear variation of control power with stick travel. On the right are the on-off controls which apply full control power or rocket thrust when the control stick reaches a certain position. The proportional control gave trouble because of the difficulty of avoiding small amounts of control application with the stick centered. This problem was eliminated by the addition of a dead spot at the center of the stick to cut off rocket thrust until the stick was moved to approximately 20 percent of travel. It was found that with either of the linear configurations pilots did not use the proportionality features since control inputs consisted predominantly of maximum thrust of short duration. The pilots, in effect, were using the proportional control as an on-off type of control. The pilots reported little difference between the on-off and the proportional control. A relatively short learning period was required to become proficient with either control, and the pilots believed that control was not too difficult. However, they did require almost constant use of the reaction controls to make small trim corrections. The two-step, on-off control was preferred over the one step, but, for simplicity, the one-step control configuration was used for the rest of the investigation.

Since the reaction-control inputs were of a very short duration, it was believed that any time lag of thrust buildup or cutoff at control application might have some effect on control. However, an investigation of time lags up to 0.5 second showed that this lag does not have a significant effect on control.

Early in the investigation, it was found that pilots desired more roll-control power than pitch- or yaw-control power. Therefore, many combinations of control effectiveness were investigated. The results are presented in figure 4 which shows the variation of thrust impulse per second of flight with roll-control effectiveness for various ratios of roll to pitch-control effectiveness or roll to yaw-control effectiveness. Roll-control effectiveness was arbitrarily selected for comparison purposes. Impulse per second is a summation of the reaction-control impulse about all three axes divided by the run duration time. Impulse per second is used not only to show the thrust required but also as an indication of efficiency of the various control combinations. Control effectiveness is expressed in terms of the constant angular acceleration produced by the reaction controls.

The ratio of roll to pitch or yaw control was varied from 1:2 to 8:1. In general, more satisfactory control was obtained at the lower control effectiveness regions. These levels were high enough to allow fairly large disturbances to be controlled and were also satisfactory for trimmed flight conditions requiring small control applications. Increased control effectiveness tended to produce overcontrol and more difficulty in flying and a corresponding increase in impulse.

The pilots preferred ratios of 2:1 to 4:1 and roll-control levels of about  $5^\circ/\text{sec}^2$  or  $10^\circ/\text{sec}^2$ . This is summarized in figure 5 which presents regions of satisfactory and unsatisfactory control for various combinations of roll-control effectiveness and control-effectiveness ratio. The shaded areas indicate the regions investigated. Regions of satisfactory and unsatisfactory control characteristics are shown. The two preferred conditions are indicated by the symbols. Although no data were obtained at lower control-effectiveness levels, the satisfactory area probably extends slightly into this region.

The investigation was next extended to include aerodynamic effects at dynamic pressures up to 10 lb/sq ft. The basic investigation was for the aerodynamic derivatives of the X-1B at a Mach number of 0.5. The pilots' display was modified from the condition at  $q = 0$  to provide the pilot with an accurate indication of  $\alpha$  and  $\beta$ . Control at low dynamic pressure was more difficult than for  $q = 0$  primarily because it was necessary to maintain sideslip angle near zero. If the pilot allowed an appreciable sideslip angle to develop, the dihedral effect produced rolling moments that required considerable roll control to counteract. Therefore, the pilots flew a very precise yaw control.

The effects of changes in directional stability and in effective dihedral were also investigated. The pilots reported a marked increase in ease of control as effective dihedral was decreased, and at  $C_{l\beta} = 0$  control was similar to that at  $q = 0$ . Reductions in directional stability had less effect on control, and adequate control was maintained even at negative values of directional stability although considerable more pilot's effort was required.

In order to carry the reaction-control studies one step further, a ground simulator was constructed. It was hoped to approximate more closely the pilots' environment and to provide a check for the analog program. Figure 6 shows the simulator in operation. The simulator is pivoted at the supporting strut and is free to rotate around three axes. The center of gravity is at the pivot point, and the pilots' position ahead of the center of gravity is similar to his location on the X-1B airplane. The pilot operates the simulator through a side-arm control stick. The simulator is operated by nitrogen gas which is exhausted out nozzles that simulate the rocket units. Carbon dioxide is shown in the photograph (fig. 6) to illustrate the operation of the simulator.

In general, the simulator tests have verified the analog results as to control-effectiveness levels desired by pilots. It will be further used to evaluate the airplane components for the rocket units and to evaluate pilot presentation and control-stick configurations.

In conclusion, it might be pointed out that, over the range of variables investigated to date, no serious difficulties as to flight at zero dynamic pressure with reaction controls have been evidenced. New pilot's techniques and constant pilot's attention to control will be required. Control at low dynamic pressure will be more difficult primarily because of dihedral effect. It is believed to be important to provide pilots with considerable practice with an analog simulation before flight tests are conducted.

## AERODYNAMIC AND REACTION CONTROL REGIONS

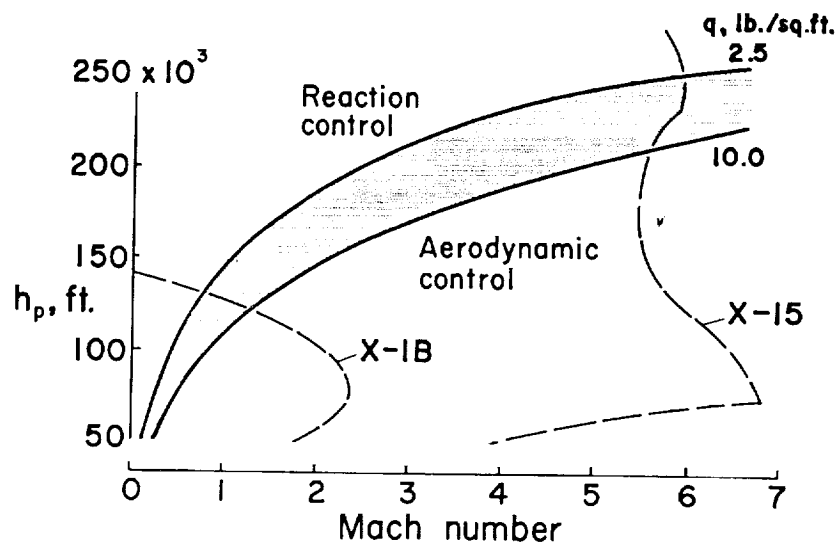


Figure 1

## ANALOG CONTROL AND PRESENTATION

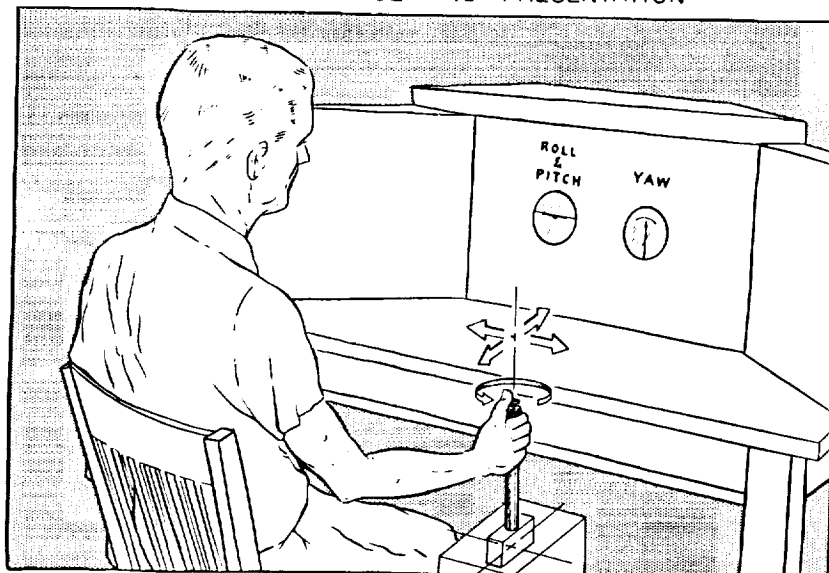


Figure 2

## CONTROL CONFIGURATIONS

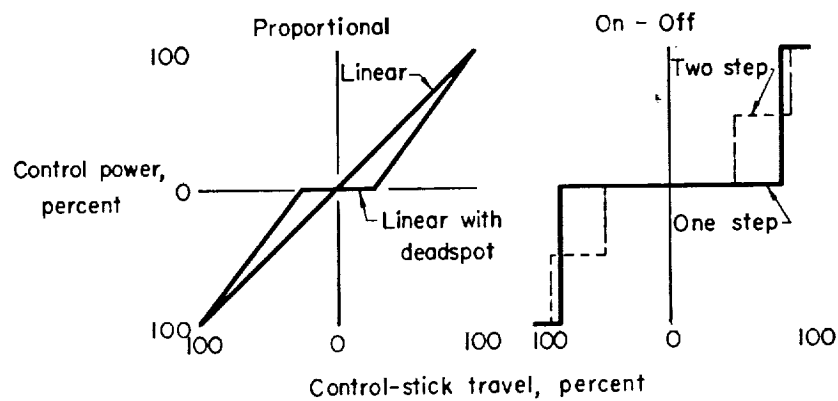


Figure 3

## FUEL REQUIREMENTS

Dynamic pressure = 0      ON-OFF Control

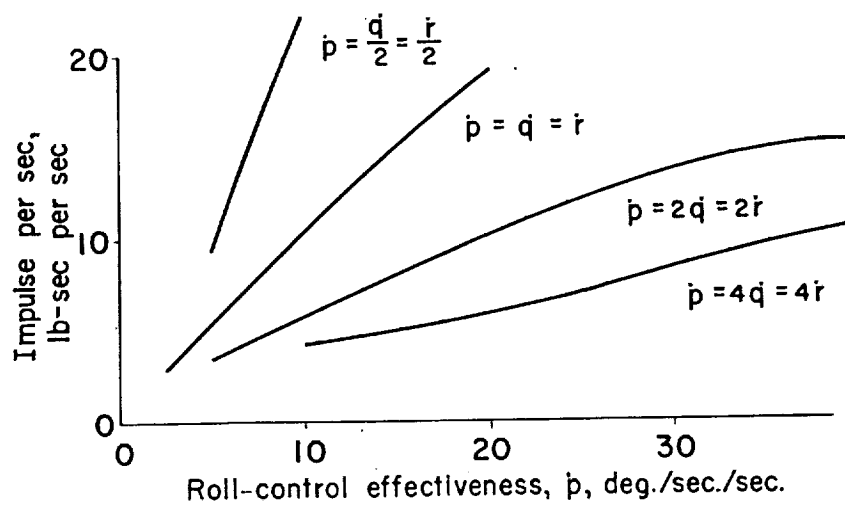


Figure 4

# PILOT-OPINION SUMMARY

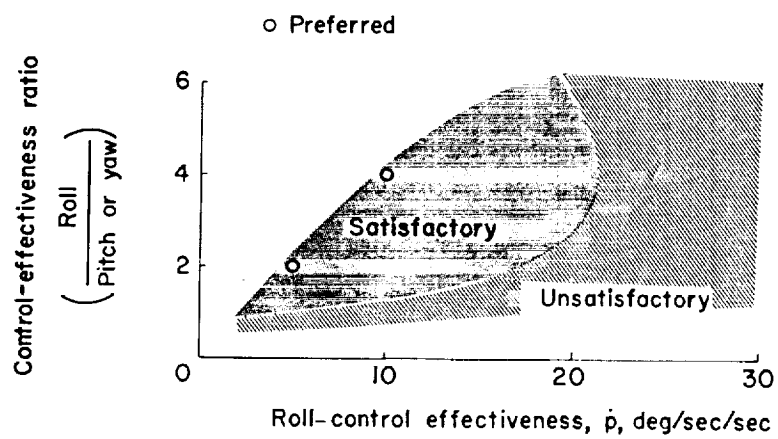


Figure 5

## ATTITUDE CONTROL SIMULATOR

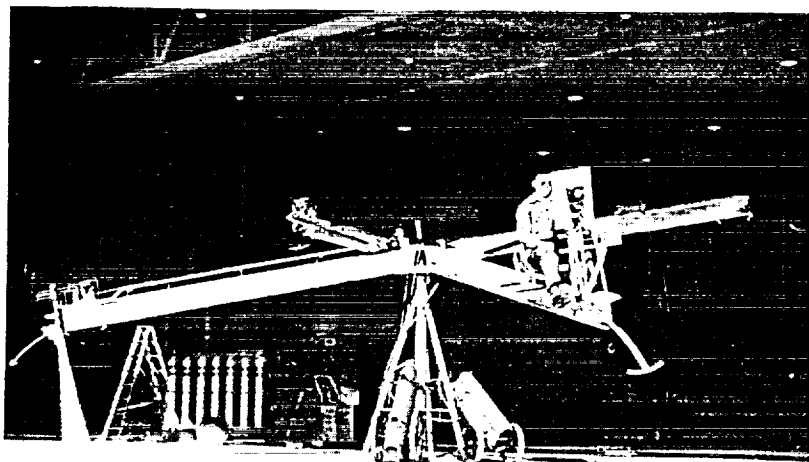


Figure 6